The TanDEM-X mission, a TerraSAR-X add-on for Digital Elevation Measurement

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Abstract- TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) is an innovative radar interferometry mission to generate a global, consistent and highly accurate Digital Elevation Model (DEM) and to provide a configurable SAR interferometry platform for demonstrating new SAR techniques and applications. This paper summarizes the mission concept starting from the user requirements, the HELIX orbit and TanDEM-X operational modes to the expected height performance and provides examples of new SAR techniques.

Keywords- *Single-pass interferometry, HRTI-3 DEM, close formation flight, new SAR techniques, TerraSAR-X*

1. INTRODUCTION

A single-pass SAR-interferometer with adjustable baselines in across- and in along-track directions is formed by adding a second (TDX), almost identical spacecraft, to TerraSAR-X (TSX) and flying the two satellites in a controlled close formation. The TanDEM-X mission has the primary objective of generating a consistent, global DEM with an unprecedented accuracy according to the HRTI-3[1] specifications. Beyond that, TanDEM-X provides the first configurable SAR interferometry platform for demonstrating new SAR techniques and applications [1], like along-track interferometry, polarimetric SAR interferometry, four phase center moving target detection, bi-static SAR imaging, and digital beamforming.

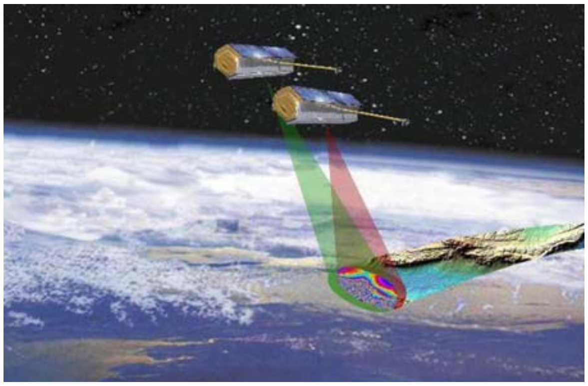

Figure 1. The TanDEM-X satellite formation.

The TDX has SAR system parameters which are fully compatible with TSX, allowing not only independent operation from TSX in a mono-static mode, but also synchronized operation (e.g. in a bi-static mode). The main differences to the TerraSAR-X satellite are the more sophisticated propulsion system to allow for constellation control, the additional S-band receiver to enable for reception of status and GPS position information broadcast by TerraSAR-X and the X-band inter-satellite link for phase referencing between the TSX and TDX radars (the required modifications on the TSX spacecraft have already been implemented). The TDX satellite is designed for five years of nominal operation. 3 years of joint operation with TSX will be sufficient to fulfill the TanDEM-X user requirements.

2. USER REQUIREMENTS

The collection of scientific and commercial user requirements for the TanDEM-X mission clearly demonstrates the need of a HRTI-3 DEM data set with global access (see comparison with existing DEM products in Fig. 2) for both scientific and commercial users. The majority of the geo-science areas like hydrology, glaciology, forestry, geology, oceanography, and land environment require precise and up-to-date information about the Earth's surface and its topography. Digital topographic maps are also a prerequisite for reliable navigation, and the improvements in their precision needs to keep step with advances in the performance of global positioning systems.. For commercial exploitation, DEMs and ortho-rectified images are the most important products for a growing earth observation market.

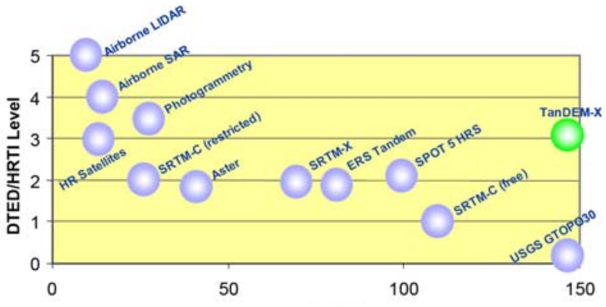

Figure 2. HRTI-level versus coverage indicating the uniqueness of the global TanDEM-X HRTI-3 product.

From a comprehensive user survey, three standard data products have been derived: standard HRTI-3 DEMs, Customised DEMs (CDEM) with even higher height resolution or improved horizontal spacing and Radar Data Products (RDP) acquired by along-track interferometry or new SAR techniques. Both scientific and commercial user requirements can be satisfied by these products and by the formation and coverage concept.

[1] HRTI-3 specification: relative vertical accuracy 2 m (90% linear point-to-point error over 1^ox1^o cell), absolute vertical accuracy 10 m (90% linear error), absolute horizontal accuracy 10 m (90% circular error), post spacing 12 m x 12 m.

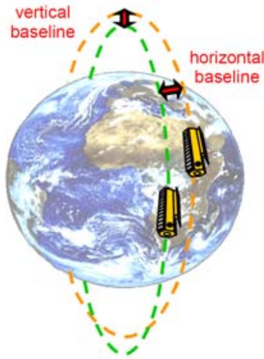

Figure 3. Artist's view of HELIX orbit concept used for TanDEM-X

3. ORBIT CONCEPT

The TanDEM-X mission concept is based on a coordinated operation of two spacecraft flying in close formation [2]. Using two spacecraft provides the highly flexible and reconfigurable imaging geometry required for the different mission objectives. For example, the primary goal of generating a highly precise HRTI-3 DEM requires variable cross-track baselines in the order of 200 to 600 m.

In this close formation flight collision avoidance becomes a major issue and a minimum safety separation of 150 m perpendicular to the flight direction has to be maintained around the orbit at any time. A formation, which fulfils these requirements, is the Helix formation shown in Fig. 3. By an adequate eccentricity/inclination-vector separation, the two satellite orbits can be controlled accurately enough to ensure the minimum safety distance with negligible low risk. Exposed to the forces of the Earth's geoid, the two satellites start to move around the frozen eccentricity, resulting in a motion of libration [2]. This effect can be advantageously used to achieve the desired baselines. The phase of libration can be adjusted by orbit maneuvers, keeping the satellites at any desired phase with low fuel costs.

4. OPERATIONAL MODES

Interferometric data acquisition with the TanDEM-X satellite formation can be achieved in three different operational modes: Bistatic, Monostatic, and Alternating Bistatic Mode [1]. Operational DEM generation is planned to be performed using bistatic single pass interferometry (Bistatic Mode), which is characterized by the illumination of a scene by one transmitter and the simultaneous measurement of the same scene with two receivers (see Fig. 4), thereby avoiding temporal decorrelation. To provide sufficient overlap of the Doppler spectra, less than 2 km along-track baselines are required while the effective across-track baselines for high resolution DEMs have to be in the order of 300 m. Over moderate terrain one complete coverage with such across-track baselines would be sufficient, but for mountainous areas (about 10% of the Earth land surface) additional data acquisitions with different baselines and viewing geometry are required. Phase unwrapping problems can be solved step-by-step acquiring two or more data sets with decreasing baseline (increasing height of ambiguity). Because of the slight differences in the Ultra Stable Oscillator (USO) characteristics of the two instruments, PRF synchronization and relative phase referencing between the satellites (exchange of USO signals via a dedicated X-band inter-satellite link) are mandatory in this mode.

The Radar Data Mode has been introduced as a synonym for the demonstration of innovative SAR modes and applications, offering a large variety of geometric constellations and of radar instrument settings (these are all SAR modes including 2 + 2 receive phase centers). The instruments are commanded according to the parameters selected by the scientists for Along-Track Interferometry (ATI) applications and for demonstration of new SAR techniques.

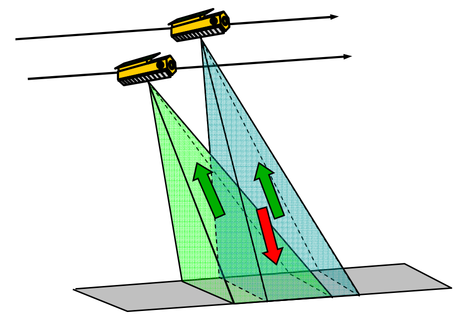

Figure 4. TanDEM-X in bistatic mode: one satellite transmits and both receive the echoes simlutaneously.

5. SYNCHRONIZATION

In Bistatic Mode the TanDEM-X interferometer is operated with two independent oscillators. Uncompensated oscillator noise will cause a slight deterioration of the bistatic impulse response, a significant shift of the bistatic SAR impulse response, and substantial interferometric phase errors in case of bistatic interferometric operation. To correct for these phase errors and also to enable pulse repetition interval (PRI) synchronization, the TanDEM-specific SAR instrument features provide a scheme for transmission and reception of USO phase information between the SARs with adequate SNR. On both the TDX and TSX-1 spacecraft six synchronization horn antennas are added at selected positions to ensure full solid-angle coverage with low phase disturbance. The required precise phase referencing for DEM generation in bistatic interferometry mode can be achieved using synchronization pulses with a PRF in the order of 10-20 Hz. For a SNR of 30 dB (a reasonable assumption for along-track displacements up to 1 km) the residual interferometric phase error can be reduced to below 1°.

6. DEM PERFORMANCE

A detailed height performance model has been developed for the Bistatic Mode covering the relative height error estimates, the calibration concept and the absolute error predictions.

A. *Relative Height Error Estimation*

The performance prediction for the relative height error is based on the following random error contributions:

- Noise due to the limited SNR during SAR data acquisition and interferogram generation, quantization errors from block adaptive quantization, limited co-registration accuracy and processing errors, as well as range and azimuth ambiguities. Decorrelation due to thermal noise in the instruments dominates this error contribution. The achievable error reduction is mainly limited by the maximum baseline (minimum height of ambiguity) that can be handled in the phase unwrapping process. Heights of ambiguity below 40 m and corresponding perpendicular baselines between 150 m and 400 m are required to reduce this error contribution to a relative height error below 2 m.

- Interferometric phase errors caused by the residual errors in the phase referencing via the noisy synchronization link.
- Random contributions from the TSX and TDX internal calibrations and uncompensated phase drifts along a data take also affecting the synchronization link.
- 3-D baseline estimation errors causing primarily a systematic phase/height ramp in the cross-track direction (~0.3 cm/km for a height of ambiguity of 35 m and a baseline estimation error in line of sight of 1 mm).

A combination of all these error sources yields the predicted relative height accuracy as shown in Fig. 5. The predicted point-to-point height errors are below 2 m for the full performance range of TSX (and TDX) which ranges from 20° incidence angle up to 45° incidence angle.

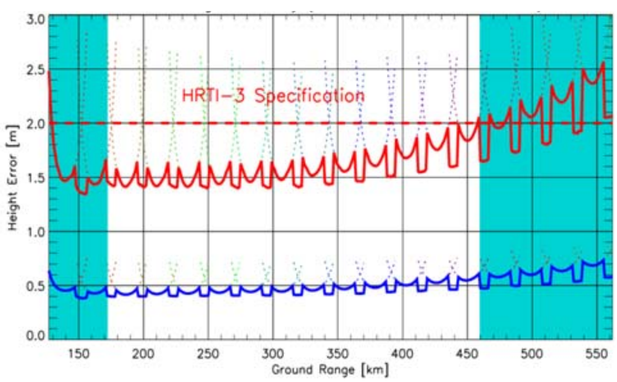

Figure 5. Predicted relative height errors for a height of ambiguity of 35 m. The red curve shows the predicted point-to-point height errors at a 90% confidence level. The blue curve represents the predicted standard deviation of the relative height errors.

B. Height Calibration Concept

The absolute height accuracy is mainly driven by the distribution and accuracy of reference height information, the calibration and mosaicking concept and the data acquisition strategy. Long continuous data takes up to 2000 km length are preferred to avoid additional errors from scene concatenation. The current calibration concept foresees the following steps:

- The generation of "raw" DEMs using SRTM heights or even lower-resolution DEMs as reference (absolute accuracy of the reference data has to be sufficient to resolve the height of ambiguity interval).
- Evaluation of swath overlaps in these raw DEMs (6 km overlap between the currently used TerraSAR-X swaths) for consistency checks between acquisitions, along-track error reduction and across-track tilt correction.
- A bundle adjustment based on the analysis of relative deviations between raw DEMs and absolute calibration references over large areas, up to continental size. Relative references can be derived from overlap areas with crossing tracks and from the previously mentioned swath overlaps. Adequate crossing tracks have to be included in the reference mission scenario. Additionally, absolute references like highly accurate DEMs from LIDAR, photogrammetry, other SAR systems, GPS tracks, spaceborne laser and radar altimeters are required. Ocean surfaces might be used as well, if their reflectivity is high enough and if they are imaged with a short along-track baseline to minimize decorrelation. The output of this step, which depending on the amount of errors might require iterations of the raw DEM generation step, is the final DEM.

C. Absolute Height Error Estimation

The HRTI-3 standard requires for the absolute height accuracy a value of 10 m at a 90% confidence level. On top of the above presented relative height errors, which contribute as a random component, the following error sources have to be considered in predicting the absolute height error:

- Accuracy of the interferometric baseline (between the SAR antenna phase centers) with contributions from the GPS differential carrier phase measurements. Investigations with data from the GRACE mission confirmed that the relative vector between the spacecraft's center of mass can be determined to within 1 mm.
- The knowledge of the satellite's attitude and the SAR antenna phase center, and the accuracy of the transformation from the spacecraft to the Earth fixed coordinate systems.
- Uncompensated long-term instrument phase errors due to temperature drift in the internal calibration network and the synchronization link.
- Residual errors in the bundle adjustment process and quality of the reference height information.

The estimate of the various error contributions results in an absolute height accuracy of 6.6 m demonstrating that TanDEM-X allows for the derivation of highly accurate digital elevation models according to the HRTI-3 standard and even beyond in Stripmap mode.

7. RADAR DATA MODE

The Radar Data Mode stands for any acquisition of TanDEM-X data products which are not covered by the DEM class. Examples for these new SAR techniques are along-track interferometry, polarimetric SAR interferometry, four phase center moving target indication, bistatic SAR imaging, and digital beamforming.

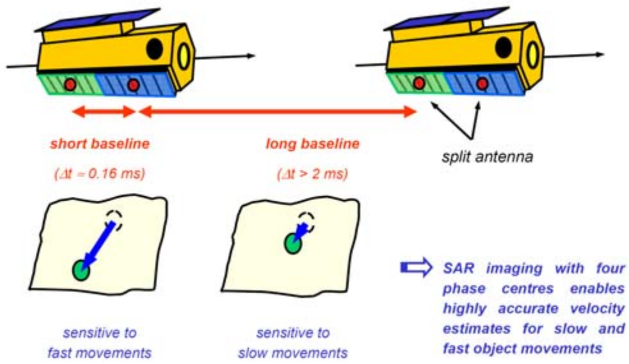

Figure 6. Along-track interferometry modes in TanDEM-X.

Along-track SAR interferometry can either be performed by the so-called dual receive antenna mode with a baseline of 2.4 m from each of the satellites or by adjusting the along-track distance of the two satellites to the desired size (see Fig. 6). The newly developed orbit concept allows this distance (called along-track baseline) to be adjusted from zero to several kilometers. This technical feature is essential as this application requires velocity measurements of different fast and slow objects. Mainly four scientific application areas are identified to explore the innovative along-track mode: oceanography, traffic monitoring, glaciology and hydrology. Of scientific interest is the identification of moving objects as well as the estimation and the validation of different velocity estimates. In all three application areas the knowledge of the velocity will improve model predictions for environmental, economical, as well as social aspects.

With TanDEM-X, innovative SAR techniques will be demonstrated and exploited, which open up new perspectives for future SAR systems. Bistatic and multistatic SAR imaging enabling enhanced scene feature extraction by combination of monostatic and bistatic signatures. Polarimetric SAR interferometry allows for precise measurements of important vegetation parameters like vegetation height and density. Digital beamforming and superresolution are key techniques for future generations of sensors. The main interest for these research areas lies in the understanding and the development of new algorithms.

8. MISSION SCENARIO

Contrary to conventional Earth Observation missions, the TanDEM-X global mapping strategy has also to account for the formation geometry, as for given HELIX parameters, DEM acquisitions are only possible for a certain latitude range. Furthermore, in the parallel operation of the TanDEM-X and TerraSAR-X missions, the latter should not be disturbed and the TanDEM-X acquisitions have to be planned as a quasi background mission.

With these constraints and the assumption of a three year tandem phase and the use of the TerraSAR-X standard Stripmap beams covering incidence angles from 20° to 45°, a reference mission scenario [2] has been developed including sufficient time slots for the acquisition of CDEMs and RDPs.

In a first phase after commissioning and first formation set-up, a global DEM is derived by monitoring the Earth at the northern hemisphere with ascending orbits and the southern hemisphere with descending orbits. The respective formations are adopted such that the required height of ambiguity fits to the respective mapping region. In the next mission phase, the formation will be shifted by 180° in phase (which corresponds to an ‘exchange’ of the satellites) and the resulting formation acquires “crossing tracks” on descending orbits on the northern, and ascending orbits on the southern hemisphere. Then DEM generation is performed for terrain which requires additional data. In the next mission phase, the satellites will be separated in along-track e.g. for bistatic monitoring and ATI experiments. Finally, the satellites will be separated at the end of the mission to a distance, where the ground track separation in the Earth fixed frame is one day, to perform further ATI experiments. In any phase, orbital periods, which are not required for deriving the global DEM, will be used for generation of CDEMs or RDPs.

9. SUMMARY

The TanDEM-X mission encompasses scientific and technological excellence in a number of aspects, including the first demonstration of a bistatic interferometric satellite formation in space, as well as the first demonstration of close formation flying in operational mode. Several new SAR techniques will also be demonstrated for the first time, such as digital beamforming with two satellites, single-pass polarimetric SAR interferometry, as well as single-pass along-track interferometry with varying baseline.

The TanDEM-X mission has been approved for full implementation. The Space Segment has recently passed the Critical Design Review (Phase C) and the Groundsegment has passed the Priliminary Design Review (Phase B). The launch of the TDX satellite is planned for spring 2009.

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